VCSEL WITH ION-IMPLANTED CURRENT-CONFINEMENT STRUCTURE

CLAIMS

What is claimed is:

1. A method for fabricating a surface-emitting laser having current confinement, the method comprising the steps of:

   (a) providing a first laser portion having a substrate, a semiconductor active region, and a bottom mirror disposed between the substrate and the active region;

   (b) epitaxially growing a first top spacer layer on the active region, the first top spacer layer comprising a current-spreading buffer layer disposed on the active region, a current-confinement layer disposed on the buffer layer, and a current-spreading platform layer disposed on the current-confinement layer, wherein the combined thickness of the platform and current-confinement layers is less than the thickness of the buffer layer;

   (c) forming, in the current-confinement layer, a current-confinement structure having an annular region of enhanced resistivity and a central aperture of comparatively lower resistivity, said step of forming comprising the step of performing ion implantation; and

   (d) after said forming of the current-confinement structure, performing epitaxial regrowth to form a top current-spreading layer.

2. The method of claim 1, wherein the surface-emitting laser is a vertical-cavity surface-emitting laser designed to emit coherent light having a wavelength of about 1550nm.

3. The method of claim 1, wherein said platform layer and said substrate consist of InP and said current-confinement layer consists of one of InAlAs and InGaAlAs.

4. The method of claim 1, further comprising the step of forming a top mirror disposed axially above the first top spacer layer to complete a resonant cavity surrounding the active region.

5. The method of claim 4, wherein the top mirror is a DBR having a plurality of mirror pairs.

6. The method of claim 5, wherein the DBR is a dielectric DBR having a plurality of dielectric mirror pairs, wherein said step of forming said dielectric DBR comprises the step of depositing said dielectric mirror pairs.

7. The method of claim 5, wherein the DBR is a semiconductor DBR having a plurality of semiconductor mirror pairs, wherein said step of forming said semiconductor DBR comprises the step of epitaxially regrowing said semiconductor mirror pairs.

8. The method of claim 1, further comprising the step of:

(e) forming a metal contact on the laser so that the metal contact is electrically coupled with the top current-spreading layer, wherein:

the top current-spreading layer and the platform layer together are sufficiently conductive to conduct pumping current from the metal contact laterally through the combined top current-spreading layer and platform layer to the central aperture of the current-confinement structure; and

the annular region has an enhanced resistivity sufficiently greater than that of the central aperture so that at least about 70% of the pumping current from the metal contact conducted through the top current-spreading layer and platform layer is blocked by the annular region and forced through the central aperture.

9. The method of claim 8, further comprising the step of forming a top mirror disposed axially above the first top spacer layer to complete a resonant cavity surrounding the active region.

10. The method of claim 9, wherein the top mirror is a DBR having a plurality of mirror pairs.

11. The method of claim 9, wherein the surface-emitting laser is a vertical-cavity surface-emitting laser designed to emit coherent light having a wavelength of about 1550nm.

12. The method of claim 8, further comprising the step of:

(f) forming a contact-facilitating layer on the top current-spreading layer by performing epitaxial regrowth;

wherein step (e) comprises the step of forming the metal contact on the contact-facilitating layer, whereby the metal contact is electrically coupled with the top current-spreading layer via the contact-facilitating layer.

13. The method of claim 8, wherein the resistance of the annular region to the pumping current conducted through said top current-spreading layer and said platform layer from the metal contact is sufficiently greater than the resistance of the central aperture to said pumping current so that most of said pumping current flows through the central aperture.

14. The method of claim 13, wherein the resistance of the annular region to the pumping current is at least about 50 times greater than the resistance of the central aperture to said pumping current.

15. The method of claim 13, wherein at least 70% of the pumping current flows through the central aperture instead of through the annular region of enhanced resistivity.

16. The method of claim 8, wherein said platform layer consists of InP.

17. The method of claim 16, wherein said substrate consists of InP and said current-confinement layer consists of one of InAlAs and InGaAlAs.

18. The method of claim 16, wherein:

the active region has InGaAsP/InP layers and comprises a plurality of quantum wells which provide a gain spectrum suitable for emitting radiation at a desired wavelength; and

the bottom mirror is a semiconductor DBR having a plurality of semiconductor mirror pairs.

19. The method of claim 8, wherein:

electrically-conducting semiconductor layers below the active region are doped to have a first conductivity type and electrically-conducting semiconductor layers above the active region are doped to have a second conductivity type opposite to the first conductivity type;

the first laser portion further comprises a bottom spacer layer disposed between the active region and the bottom mirror; the bottom mirror is a bottom semiconductor DBR;

the electrically-conducting semiconductor layers below the active region comprise the substrate, the bottom DBR, and the bottom spacer; and

the electrically-conducting semiconductor layers above the active region comprise the first top spacer layer, and the top current-spreading layer.

20. The method of claim 1, wherein said platform layer consists of InP.

21. The method of claim 1, wherein the first laser portion further comprises a bottom spacer layer disposed between the active region and the bottom mirror.

22. The method of claim 1, wherein said ion implantation of step (c) employs an implant energy of less than 400keV.

23. The method of claim 22, wherein said ion implantation of step (c) employs oxygen as an implanted species.

24. The method of claim 23, wherein the resistance of the annular region to current conducted through said top current-spreading layer and said platform layer is sufficiently greater than the resistance of the central aperture to said current so that at least about 70% of said current flows through the central aperture .

25. The method of claim 1, wherein the resistance of the annular region to current conducted through said top current-spreading layer and said platform layer is sufficiently greater than the resistance of the central aperture to said current so that at least about 70% of said current flows through the central aperture.

26. The method of claim 1, wherein the combined thickness of the platform and current-confinement layers is less than one-third of the thickness of the buffer layer.

27. The method of claim 1, wherein:

the substrate and layers disposed thereon are part of a wafer sample;

said step (d) further comprising the step of thermally annealing the sample, after said ion implantation, to correct damage to the crystal lattice of the platform layer caused by said ion implantation.

28. The method of claim 1, wherein:

the substrate and layers disposed thereon are part of a wafer sample; and

the epitaxial regrowth of step (d) is performed with heat sufficient to thermally anneal the sample to correct damage to the crystal lattice of the platform layer caused by said ion implantation.

29. The method of claim 1, wherein the central aperture has either a substantially elliptical or rectangular cross-section to cause polarization of the output of the laser.

30. The method of claim 1, wherein the substrate and layers disposed thereon are part of a wafer sample, further wherein said forming of the current-confinement structure results in native oxide being formed on a top surface of the platform layer, the method further comprising the step of:

(e) after said forming of the current-confinement structure but before performing the epitaxial regrowth of step (d), removing the native oxide from the surface of the platform layer by at least one of desorption, in-situ etching, and in-situ cleaning.

31. The method of claim 1, wherein the first top spacer layer and a second top spacer layer comprising the top current-spreading layer form a composite top spacer layer, the composite top spacer layer having a thickness selected so as to optimally position the active region axially within the laser structure.

32. A method for fabricating a surface-emitting laser having current confinement, the method comprising the steps of:

(a) providing a first laser portion having a substrate, a semiconductor active region, and a bottom mirror disposed between the substrate and the active region;

(b) epitaxially growing a first top spacer layer on the active region, the first top spacer layer comprising a current-spreading buffer layer disposed on the active region and a current-confinement layer disposed on the buffer layer;

(c) forming, in the current-confinement layer, a current-confinement structure having an annular region of enhanced resistivity and a central aperture of comparatively lower resistivity, said step of forming comprising the step of performing ion implantation; and

(d) after said forming of the current-confinement structure, performing epitaxial regrowth to form a top current-spreading layer on the current-confinement layer.

33. The method of claim 32, wherein the thickness of the current-confinement layer is less than one-third of the thickness of the buffer layer.

34. The method of claim 32, further comprising the steps of:

(e) performing epitaxial regrowth to form a contact-facilitating layer on the top current-spreading layer;

(f) forming a metal contact on the contact-facilitating layer, wherein:

the contact-facilitating layer is for electrically coupling the metal contact to the top current-spreading layer;

the top current-spreading layer is sufficiently conductive to conduct pumping current from the metal contact laterally through the top current-spreading layer to the central aperture of the current-confinement structure; and

the annular region has an enhanced resistivity sufficiently greater than that of the central aperture so that most of the pumping current from the metal contact conducted through the top current-spreading layer is blocked by the annular region and forced through the central aperture; and

(g) forming a top mirror disposed axially above the first top spacer layer to complete a resonant cavity surrounding the active region.

35. The method of claim 34, wherein the resistance of the annular region to the pumping current conducted through said top current-spreading layer from the metal contact is sufficiently greater than the resistance of the central aperture to said pumping current so that at least about 70% of said pumping current flows through the central aperture instead of through the annular region of enhanced resistivity.

36. The method of claim 32, wherein said platform layer and said substrate consist of InP and said current-confinement layer consists of one of InAlAs and InGaAlAs.

37. The method of claim 32, wherein said ion implantation of step (c) employs an implant energy of less than 400keV and employs oxygen as an implanted species.

38. The method of claim 32, wherein:

the substrate and layers disposed thereon are part of a wafer sample;

said step (d) further comprising the step of thermally annealing the sample, after said ion implantation, to correct damage to the crystal lattice of the platform layer caused by said ion implantation.

39. A method for fabricating a surface-emitting laser having current confinement, the method comprising the steps of:

(a) providing a first laser portion having a substrate, a semiconductor active region, and a bottom mirror disposed between the substrate and the active region;

(b) epitaxially growing a top spacer layer on the active region, the top spacer layer comprising a current-spreading buffer layer disposed on the active region, a current-confinement layer disposed on the buffer layer, and a current-spreading platform layer disposed on the current-confinement layer, wherein the combined thickness of the platform and current-confinement layers is less than the thickness of the buffer layer;

(c) forming, in the current-confinement layer, a current-confinement structure having an annular region of enhanced resistivity and a central aperture of comparatively lower resistivity, said step of forming comprising the step of performing ion implantation; and

(d) forming a contact-facilitating layer on the platform layer.

40. The method of claim 39, wherein the step (d) comprises the step of epitaxially regrowing the contact-facilitating layer on the platform layer after step (c), the method further comprising the steps of:

(e) forming a metal contact on the contact-facilitating layer, wherein:

the contact-facilitating layer is for electrically coupling the metal contact to the platform layer;

the platform layer is sufficiently conductive to conduct pumping current from the metal contact laterally through the platform layer to the central aperture of the current-confinement structure; and

the annular region has an enhanced resistivity sufficiently greater than that of the central aperture so that most of the pumping current from the metal contact conducted through the platform layer is blocked by the annular region and forced through the central aperture; and

(g) forming a top mirror disposed axially above the first top spacer layer to complete a resonant cavity surrounding the active region.

41. The method of claim 40, wherein the resistance of the annular region to the pumping current conducted through said platform layer from the metal contact is sufficiently greater than the resistance of the central aperture to said pumping current so that at least about 70% of said pumping current flows through the central aperture instead of through the annular region of enhanced resistivity.

42. The method of claim 40, wherein said platform layer and said substrate consist of InP and said current-confinement layer consists of one of InAlAs and InGaAlAs.

43. The method of claim 39, wherein said ion implantation of step (c) employs an implant energy of less than 400keV and employs oxygen as an implanted species.

44. The method of claim 39, wherein the step (d) comprises the step of epitaxially regrowing the contact-facilitating layer on the platform layer after step (c).

45. The method of claim 44, wherein the combined thickness of the platform and current-confinement layers is less than one-third of the thickness of the buffer layer.

46. The method of claim 39, wherein:

step (d) comprises the step of epitaxially growing the contact-facilitating layer on the platform layer after step (b) and before step (c); and

the combined thickness of the platform, current-confinement, and contact-facilitating layers is less than the thickness of the buffer layer.

47. The method of claim 39, wherein:

step (d) comprises the step of epitaxially growing the contact-facilitating layer on the platform layer after step (b) and before step (c); and

the combined thickness of the platform, current-confinement, and contact-facilitating layers is less than one-third of the thickness of the buffer layer.

48. A surface-emitting laser formed in accordance with the method of claim 1.

49. A surface-emitting laser formed in accordance with the method of claim 32.

50. A surface-emitting laser formed in accordance with the method of claim 39.

51. A surface-emitting laser comprising:

(a) a first laser portion having a substrate, a semiconductor active region, and a bottom mirror disposed between the substrate and the active region;

(b) a composite top spacer layer disposed on the active region; and

(c) a top mirror disposed axially above the top spacer layer to complete a resonant cavity surrounding the active region, wherein the top spacer layer comprises a current-spreading buffer layer disposed on the active region, a current-confinement layer disposed on the buffer layer, and a second current-spreading layer disposed on the current-confinement layer, the current-confinement layer comprising a current-confinement structure having an ion-implanted annular region of enhanced resistivity and a central aperture of comparatively lower resistivity, wherein the buffer layer is no more than about 10,000Å thick, wherein the current-confinement layer consists of a

material able to acquire enhanced resistivity when subjected to ion implantation and subsequent thermal annealing that serves to reduce damage to the crystal lattice of the current-confinement layer caused by said ion implantation.

52. The laser of claim 51, wherein the buffer layer is no more than about 4500Å thick.

53. The laser of claim 51, wherein the buffer layer is no more than about 3000Å thick.

54. The laser of claim 51, wherein said second current-spreading layer comprises a current-spreading platform layer disposed on said current-confinement layer and a top current-spreading layer disposed on said platform layer.

55. The laser of claim 54, wherein said platform layer is epitaxially grown on said current-confinement layer before formation of said current-confinement region and the top current-spreading layer is epitaxially regrown on said current-confinement layer after formation of said current-confinement region.

56. The laser of claim 54, wherein said buffer layer is at least about three times the combined thickness of the current-confinement and platform layers.

57. The laser of claim 54, further comprising:

(d) a contact-facilitating layer disposed on the top current-spreading layer; and

(e) a metal contact disposed on the contact-facilitating layer; wherein:

the contact-facilitating layer is for electrically coupling the metal contact to the top current-spreading layer;

the top current-spreading layer and the platform layer together are sufficiently conductive to conduct pumping current from the metal contact laterally

through the combined top current-spreading layer and platform layer to the central aperture of the current-confinement structure; and

the annular region has an enhanced resistivity sufficiently greater than that of the central aperture so that most of the pumping current from the metal contact conducted through the top current-spreading layer and platform layer is blocked by the annular region and forced through the central aperture.

58. The laser of claim 57, wherein the resistance of the annular region to the pumping current conducted through said top current-spreading layer and said platform layer from the metal contact is sufficiently greater than the resistance of the central aperture to said pumping current so that at least about 70% of said pumping current flows through the central aperture instead of through the annular region of enhanced resistivity.

59. The laser of claim 57, wherein the surface-emitting laser is a vertical-cavity surface-emitting laser designed to emit coherent light having a wavelength of about 1550nm.

60. The laser of claim 57, wherein said platform layer and said substrate consist of InP and said current-confinement layer consists of one of InAlAs and InGaAlAs.

61. The laser of claim 57, wherein the combined thickness of the platform and current-confinement layers is less than one-third of the thickness of the buffer layer.

62. The laser of claim 51, wherein said current-confinement layer material is able to acquire said enhanced resistivity when subjected to ion implantation and subsequent higher-temperature processing in the range of about 450°C to 700°C.

63. The laser of claim 51, wherein said current-confinement layer material comprises aluminum and said buffer layer and said second current-spreading layer do not comprise aluminum.

64. The laser of claim 51, wherein the active region is substantially free of ion implantation straggle damage.

65. The laser of claim 51, wherein the current-confinement structure has been formed employing ion implantation with an implant energy of less than 400keV.

66. A surface-emitting laser comprising:

(a) a first laser portion having a substrate, a semiconductor active region, and a bottom mirror disposed between the substrate and the active region;

(b) a composite top spacer layer disposed on the active region, the composite top spacer layer comprising a current-spreading buffer layer disposed on the active region, a current-confinement layer disposed on the buffer layer, and a current-spreading platform layer disposed on the current-confinement layer, wherein the combined thickness of the platform and current-confinement layers is less than the thickness of the buffer layer, the current-confinement layer comprising a current-confinement structure having an ion-implanted annular region of enhanced resistivity and a central aperture of comparatively lower resistivity, wherein the buffer layer is no more than about 10,000Å thick, wherein the current-confinement layer consists of a material able to acquire enhanced resistivity when subjected to ion implantation and subsequent higher-temperature processing;

(d) a contact-facilitating layer disposed on the platform layer; and

(e) a metal contact disposed on the contact-facilitating layer, wherein:

the contact-facilitating layer is for electrically coupling the metal contact to the platform layer;

the platform layer is sufficiently conductive to conduct pumping current from the metal contact laterally through the platform layer to the central aperture of the current-confinement structure; and

the annular region has an enhanced resistivity sufficiently greater than that of the central aperture so that most of the pumping current from the metal contact conducted through the platform layer is blocked by the annular region and forced through the central aperture; and

(f) a top mirror disposed axially above the composite top spacer layer to complete a resonant cavity surrounding the active region.

67. The laser of claim 66, wherein the resistance of the annular region to the pumping current conducted through said platform layer from the metal contact is sufficiently greater than the resistance of the central aperture to said pumping current so that at least about 70% of said pumping current flows through the central aperture instead of through the annular region of enhanced resistivity.

68. The laser of claim 66, wherein said platform layer and said substrate consist of InP and said current-confinement layer consists of one of InAlAs and InGaAlAs.

69. The laser of claim 66, wherein the combined thickness of the platform and current-confinement layers is less than one-third of the thickness of the buffer layer.

70. The laser of claim 66, wherein the combined thickness of the platform, current-confinement, and contact-facilitating layers is less than one-third of the thickness of the buffer layer.

71. The laser of claim 66, wherein the buffer layer is no more than about 3000Å thick.

72. The laser of claim 66, wherein said current-confinement layer material is able to acquire said enhanced resistivity when subjected to ion implantation and to subsequent higher-temperature processing in the range of about 450°C to 700°C.

73. The laser of claim 66, wherein said current-confinement layer material comprises aluminum and said buffer and platform layers do not comprise aluminum.

74. The laser of claim 66, wherein the active region is substantially free of ion implantation straggle damage.

75. The laser of claim 66, wherein the current-confinement structure has been formed employing ion implantation with an implant energy of less than 400keV.